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Published in:
Proceedings of META 2014

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Khromova, I., Andryieuski, A., & Lavrinenko, A. (2014). Multilayer Graphene for Waveguide Terahertz Modulator. In *Proceedings of META 2014*

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Multilayer Graphene for Waveguide Terahertz Modulator

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Abstract

We study terahertz to infrared electromagnetic properties of multilayer graphene/dielectric artificial medium and present a novel concept of terahertz modulation at mid-infrared wavelengths. This approach allows the realization of high-speed electrically controllable terahertz modulators based on hollow waveguide sections filled with multilayer graphene.

1. Introduction

Active development of terahertz/infrared science and engineering has created a growing demand for new electronic and quasi-optical devices. In the absence of mature technologies applicable to this frequency region, a huge effort is being made to investigate the opportunities offered by novel materials, such as graphene [1] and artificially created metamaterials on its base.

Due to extraordinarily high carrier mobility [2] and picosecond-scale photocarrier generation and relaxation [3], graphene has been actively studied as a solution for high-speed modulators at different frequency ranges [4]-[6].

In this work, we investigate dielectric properties of multilayer graphene as an artificial medium and present a novel concept of a terahertz modulator based on a hollow waveguide filled with graphene/dielectric composite.

2. Multilayer Graphene/Dielectric Medium

We investigate the properties of a composite shown in Fig. 1: graphene sheets are interlayered by a dielectric material of thickness d and a dielectric permittivity ϵ_M . We suppose that each pair of graphene sheets is gated by applied voltage, thus, providing the tunability of the electromagnetic parameters of the structure. Despite implying a technological challenge, such a composite was recently successfully fabricated using 100 nm-thick PMMA layers between graphene sheets [7].

Supposing d to be much smaller than the wavelength of the terahertz/infrared radiation, we can characterize the structure by an effective dielectric permittivity:

$$\epsilon_{eff}(\epsilon_M, \omega, d, E_f, \gamma) = \epsilon_M + i \frac{\sigma(E_f, \gamma)}{\omega \epsilon_M d}, \quad (1)$$

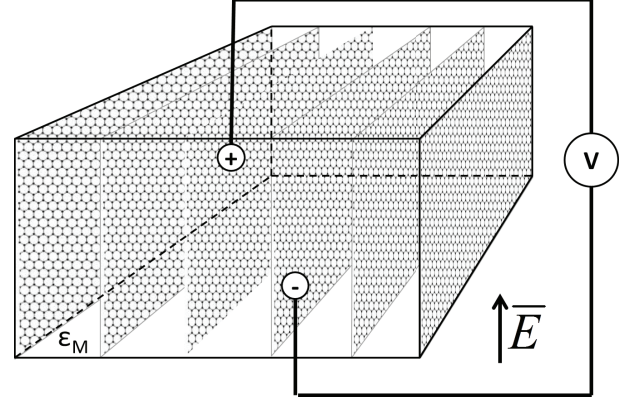


Figure 1: Tunable multilayer graphene controlled by applied gate voltage.

where ω is the angular frequency, E_f is the Fermi energy of the graphene sheets (in this work, we neglect the effects of the substrates and consider the Fermi energy of all graphene layers to be equal), γ is the graphene scattering rate set as $10^{12} s^{-1}$.

Graphene conductivity σ is calculated by the Kubo formula [8] taking the both the intraband and interband terms into account:

$$\begin{aligned} \sigma &= \sigma_{intra} + \sigma_{inter}, \\ \sigma_{intra} &= \frac{2e^2 k_B T}{\pi \hbar^2} \text{Ln}(2 \text{Cosh}(\frac{E_f}{2k_B T})) \frac{i}{\omega + i\gamma} \quad (2) \\ \sigma_{inter} &= \frac{e^2}{4\hbar} (H(\frac{\omega}{2}) + \frac{i4\omega}{\pi} \int_0^\infty \frac{H(\Omega) - H(\frac{\omega}{2})}{\omega^2 - 4\Omega^2} d\Omega) \end{aligned}$$

where e is the electron charge, \hbar is the Plank constant, k_B is the Boltzman constant, T is the temperature considered to be equal to 300K, and $H(x)$ is a function determined as in [8].

In contrast to the submillimetre band, at high terahertz frequencies graphene exhibits high conductivity and low losses. When the interband transitions kick in, the imaginary part of graphene conductivity becomes negative while its real part starts to grow. In a graphene/dielectric medium, this effect can be seen as a metal to dielectric transition followed by low-loss dielectric to high-loss dielectric transition (Fig. 2). In the vicinity of this peculiar frequency region, the real part of the effective dielectric permittivity of

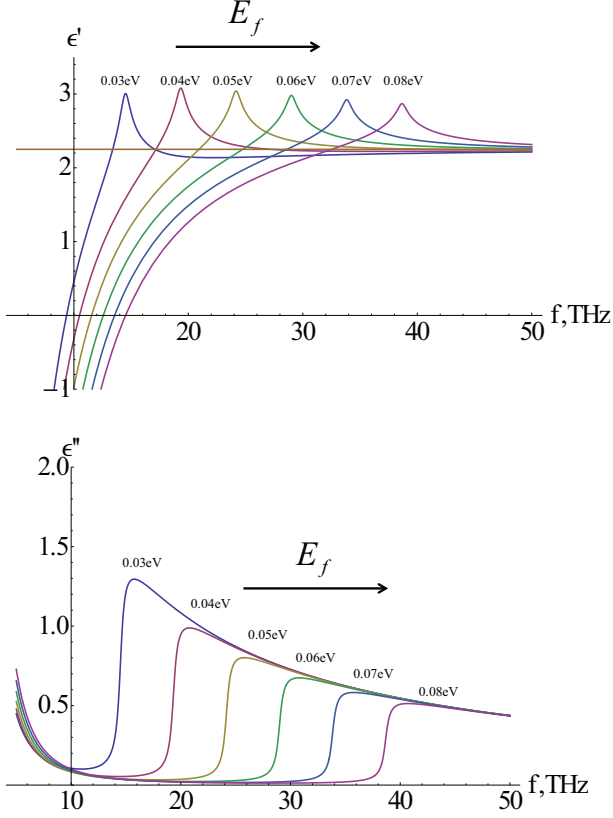


Figure 2: Real (ϵ') and imaginary (ϵ'') parts of the dielectric permittivity of the multilayer graphene medium with $d = 50\text{nm}$ and ($\epsilon_M = 2.25$) at different Fermi energy levels.

the structure exceeds the host medium permittivity ϵ_M . As the frequency increases, the medium becomes lossier and less optically dense.

The frequency at which this spectrally narrow change in macroscopic electromagnetic properties takes place is extremely sensitive towards changes in the concentration of charge carriers in graphene layers. The latter is governed by gate voltage.

In this paper, we suggest using this phenomenon to achieve electrically controllable modulation in hollow waveguides filled with graphene/dielectric medium.

3. Hollow waveguide filled with graphene/dielectric composite

At mid-infrared wavelengths, where both ohmic and dielectric losses are present, hollow waveguides are considered as the optimal solution for transferring radiation [9, 10]. We consider a rectangular hollow waveguide filled with multilayer graphene and demonstrate efficient electrically controllable modulation at frequencies around the CO₂ laser emission line. For simplicity, ohmic losses in the waveguide are neglected. In the on-state, the modulating waveguide section transmits the fundamental mode, which is suppressed due to dielectric to metal transition at lower frequencies and dielectric losses at higher frequencies. As

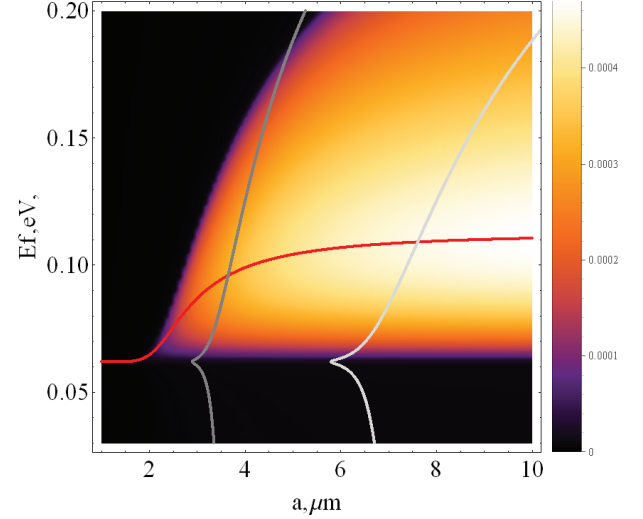


Figure 3: Inverse attenuation coefficient, α^{-1} , of a TE₁₀ mode of a graphene-filled waveguide as a function of the waveguide width a and graphene Fermi energy E_f . The red curve corresponds to the local minimum of α (α_{on}). Dark grey and light grey curves denote the cut-off conditions of the TE₁₀ and TE₂₀ modes, respectively.

discussed in the previous Section, modulation is achieved by changing the applied gate voltage.

Fig. 3 shows the analytically calculated inverse attenuation coefficient of a TE₁₀ mode of a hollow rectangular waveguide filled with multilayer graphene. For given waveguide dimensions, provided they fall between the TE₁₀ and TE₂₀ cut-off conditions, the minimum of the attenuation coefficient determines the Fermi energy level at which the highest transmission is achieved. It can be seen that a slight variation of gate voltage can dramatically change the dielectric properties of the waveguide core leading to strong attenuation of the fundamental mode.

Once the desired transmission parameter is defined, the length of the waveguide modulator section is determined as:

$$L = -\frac{1}{\alpha_{on}} T_{on} \quad (3)$$

For instance, a 95% transmission in a $5\ \mu\text{m}$ waveguide can be achieved at $L = 20.7\ \mu\text{m}$ (meaning much higher transmission for shorter modulation sections). The change of the Fermi energy level required to achieve desired modulation depth is given in Table.1. The graphene conductivity model used in this paper does not allow evaluating the modulator performance for Fermi energies below $E_{f0} \approx 0.03\ \text{eV}$.

4. Modulator design

Knowing the resulting refractive index of the graphene/dielectric composite in the on-state, n_{on} , we can use the same filling for the input and output metallic waveguides to minimize the insertion loss. Ideally, $n_{on} = 1$ can be reached if we assume certain freedom of

Table 1: Example of modulation depth calculation for $T_{on} = 0.95$, $E_f = 0.1042$ eV, $a = 5$ μm .

Fermi energy change ΔE_f , eV	normalized modulation depth $\frac{10\text{Log}(T_{on}/T_{off})}{a}$, dB μm^{-1}
0.044	0.48
0.047	0.63
>0.064	>0.71

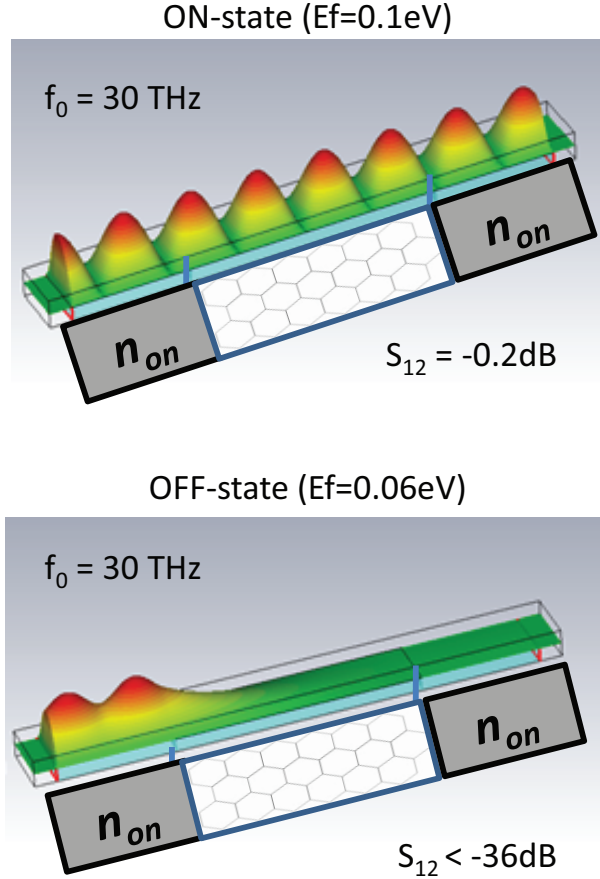


Figure 4: On- and off- state fields in a graphene-based modulator.

choice of dielectric material between graphene sheets.

Fig. 4 shows the numerically obtained electric fields propagating between the input and output metallic waveguides through the modulator section filled with multilayer graphene. This example demonstrates the performance of the novel terahertz modulator - a 0.04 eV change of the graphene Fermi energy leads to complete and quick switch between transmission and attenuation regimes.

5. Conclusions

The interplay between interband and intraband transitions in graphene allows to convert a multilayer graphene/dielectric structure into a transparent and electromagnetically dense artificial medium in a narrow mid-

infrared wavelength range. Gate voltage can be used to electrically control the concentration of carriers in the graphene sheets and, thus, efficiently change the dispersion of the whole structure. Placed inside a hollow waveguide, multilayer graphene/dielectric composite provides high-speed modulation of radiation and offers a novel concept of a terahertz modulator.

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